Composites Part A 27A (1996) 575–581

1359-835X/96/$15.00
S1359-835X(96)00029-2

Ballistic impact of fibre composite armours by fragment-simulating projectiles

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(Received 4 January 1996)

Tests have been conducted in which 1.1 g fragment-simulating projectiles (FSPs) were fired at nylon 6,6/ethylene vinyl acetate composite laminates. The laminates were manufactured at two pressing loads and two values of areal density (mass per unit area). V_{50} penetration velocities were measured and microscopic examination was conducted to gain an insight into the mechanics of penetration. This showed that the penetration is initiated by a combination of shear cutting and tensile failure that can be related to the shape of the FSP. The subsequent phase of penetration involves delamination of the composite and tensile failure of the fibres. There is a trend for laminates manufactured at a lower pressing load to absorb more impact energy. Copyright © 1996 Elsevier Science Limited.

(Keywords: composite armours; ballistic impact; fragment-simulating projectiles; penetration mechanism)

INTRODUCTION

Polymeric textile fibres made of materials such as nylon, aramid and ultra-high molecular weight polyethylene are used in the construction of clothing to give protection against ballistic attack. The fibres alone, in the form of cross-stitched, multi-layer fabrics, are used to protect the body against fragments and low-velocity handgun bullets. To protect the head, however, the fibres are contained within a polymeric matrix to make a pressed laminate that is relatively rigid. The resulting helmet shell can then, with a sufficient stand-off and a foam liner, both stop projectile penetration and prevent traumatic impact to the head.

The main ballistic threats to soldiers in battle are fragments from bombs, shells, mortars and grenades, etc.[1]. Protection against these threats is normally assessed using fragment-simulating projectiles (FSPs). The most commonly used FSP for the appraisal of body armours and helmets is a chisel-nosed steel cylinder[2,3], shown schematically in *Figure 1*. Fragments to this specification can range in mass from 0.16 to 2.8 g. By far the most common size of FSP, however, which is that used for the tests described in this paper, weighs 1.102 ± 0.02 g. It has a diameter (A in *Figure 1*) of 5.385 ± 0.02 mm, an unchamferred width (B) of 2.54 mm and a length (C) of about 6.35 mm, which is adjusted to ensure the correct mass. The FSP is made of an alloy steel with a Rockwell C hardness of 30 ± 2.

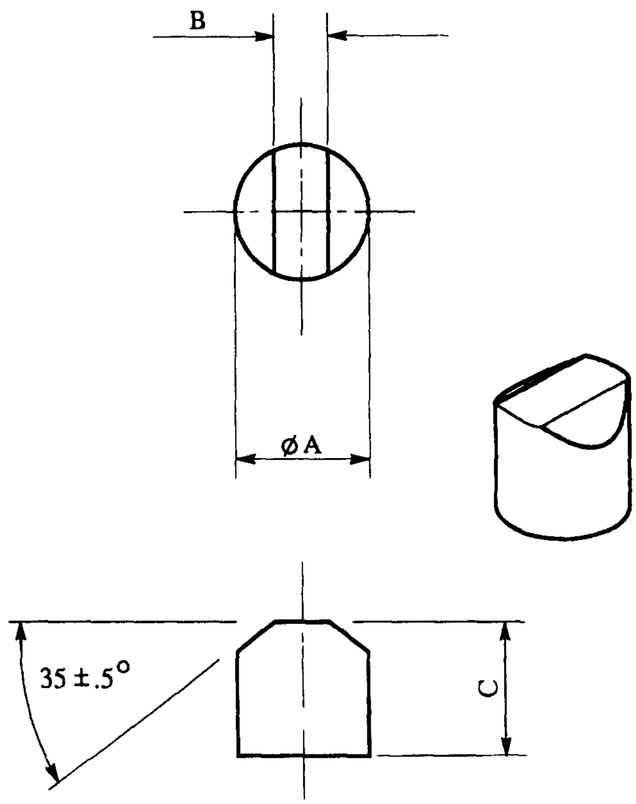

Figure 1 Fragment simulating projectile (FSP)

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Because of the innate variations involved in ballistic testing, a V_{50} ballistic limit velocity is measured. V_{50} is defined as the estimated velocity which gives a 0.5 probability of complete penetration. A complete penetration occurs if an FSP, or material thrown off the back of the armour under test, passes through a 0.5 mm thick aluminium sheet placed 150 mm behind the armour. Otherwise, the impact is termed a partial penetration. The usual estimate of V_{50} is made by averaging the three lowest complete penetration velocities and the three highest partial penetration velocities. The spread of these velocities must lie within 40 m s^{-1} (refs 2 and 3). Because the results can be variable, a minimum of three V_{50} tests should be completed for each test condition. The V_{50} test is used throughout the armour industry to compare different armour materials and systems and for quality control purposes using either test panels or actual equipment such as helmets.

One aim of this paper relates to the penetration mechanisms of fragment-simulating projectiles of the form shown in *Figure 1*. Other forms of FSP are sometimes used, such as flat- and hemispherical-ended cylinders for example, and there is a move to use steel balls for some testing in the future[4]. An understanding of the effect of fragment shape on the mechanisms of ballistic penetration is, therefore, of some importance.

A second aim of this paper is to report on tests conducted on helmet material laminates manufactured with different pressing loads. A variation in pressing load is inherent in the construction of a fibre composite laminate helmet because of the shape of the mould. The ram strikes vertically above the crown of the helmet and this point experiences the maximum pressing load. The load normal to the laminate gradually reduces towards the periphery of the helmet. It is important to know the effect of this variation on the ballistic performance of the helmet.

The failure mechanisms of textile armours have been extensively investigated[1]. Prosser[5] showed that the major mode of penetration of nylon ballistic panels when impacted by an FSP, similar to that shown in *Figure 1*, was by a cutting, shearing mechanism. He supported his ballistic test observations with an investigation of the effect of support geometry on the tensile strength of nylon and aramid yarns, which confirmed his postulation. Langlie and Cheng[6] studied the failure mode of thick S-2 glass-reinforced polyester laminates impacted by hemispherical-nosed cylindrical FSPs. They identified three different failure mechanisms through the thickness of the composite: transverse shear failure in the front layers first impacted by the projectile, tensile failure in the middle layers of the composite and delamination in the rear layers near the back of the target. A model based on these mechanisms was incorporated into the DYNA2D finite element code and reasonable correlations with experimental results were obtained. For graphite/epoxy laminates penetrated by 12.7 mm diameter steel spheres, Czarnecki[7] observed fractures similar to shear plugging adjacent to the impacted surface and delaminations near the rear surface. He proposed that the transition from shear plugging to delamination, caused by the tensile stress wave that reflects from the rear surface, occurs when the projectile interacts with the returning tensile wave. This hypothesis was supported by tests using embedded sensors.

EXPERIMENTAL METHOD AND RESULTS

Laminate manufacture

Composite laminates were made using nylon 6,6 fibres (940 dtex), plain woven into a fabric (290 g m^{-2}) and laminated with a matrix of ethylene vinyl acetate (EVA) weighing 60 g m^{-2}. Test samples, of size 250 mm × 250 mm, were made to four specifications: laminates were made with 12 and 22 plies of fabric at two pressing loads (3.5 and 20 tons, giving pressures of 0.56 and 3.20 MPa, respectively). The laminates contained a minimum of 80% by weight of fibre.

The laminates were manufactured at the Defence Clothing and Textiles Agency, Science and Technology (DCTA S&T) Division, Colchester using the following procedure. Starting with the middle ply of each sample, a backed film of EVA resin was applied to the fabric using a household iron. The backing material was then removed by peeling after the sample had cooled sufficiently and a further layer of fabric was applied, again using the iron. Layers were applied to alternate sides of the sample to minimize warping and, hence, any pre-stressing of the material. This process was repeated to make either a 12- or 22-ply laminate.

The assembled laminate was then placed between the platens of a 20 ton press which were electrically heated to 165°C before a load of 3.5 or 20 tons was applied hydraulically. Load and temperature were monitored and maintained for 30 min before the platens were cooled. When the plates reached room temperature, the pressure in the system was released and the test sample was removed.

When weighed, the finished laminates showed some weight loss compared with that calculated from the original masses of the nylon and EVA layers (approximately 5 and 9% for the 12- and 22-ply laminates, respectively). This was caused by loss of EVA by leakage and evaporation. The uniformity of distribution of the EVA, however, was verified for a 22-layer laminate sample by measurements of layer thickness which averaged 0.80 mm with a standard deviation of 0.013.

Ballistic testing

The ballistic trials were conducted in an indoor firing range at the Royal Military College of Science, Shrivenham using 1.1 g FSPs described in the Introduction and shown in *Figure 1*. The FSPs were fired from a 7.62 mm barrel mounted in a proof housing. The muzzle-to-target distance was 10 m. Each laminate target was clamped in a mild steel frame of 200 mm × 200 mm internal dimen-

Table 1 Ballistic test results

Sample	Number of layers	Pressing load (tons)	Areal density ($kg\,m^{-2}$)	Panel thickness (mm)	V_{50} ($m\,s^{-1}$)	Velocity spread ($m\,s^{-1}$)	K
1A	12	20	3.99	3.86	322.2	35.5	161.3
1B	12	20	4.00	3.83	333.6	32.3	166.8
1C	12	20	3.91	3.70	319.4	37.5	161.6
2A	22	20	7.08	7.38	464.4	39.0	174.5
2B	22	20	7.08	7.15	486.5	24.1	182.8
2C	22	20	7.07	6.82	444.9	39.6	167.3
3A	12	3.5	3.85	4.28	357.5	38.0	182.2
3B	12	3.5	3.83	4.39	376.5	37.0	192.4
3C	12	3.5	3.85	4.41	360.5	34.6	183.7
4A	22	3.5	6.83	7.75	429.1	38.1	164.2
4B	22	3.5	7.16	8.05	457.2	39.3	170.9
4C	22	3.5	7.15	8.17	457.5	37.3	171.1

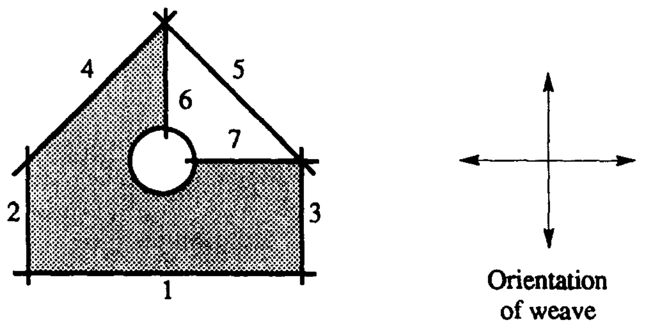

Figure 2 Orientation and sequence of cuts (1 to 7) in preparation of samples for microscopy

sions using a 'G' clamp at each corner. Projectile velocities were measured using an optical sky screen system. A pair of screens, positioned 4 m and 2 m in front of the target, triggered timers when an FSP passed between each photo-receptor screen and a light source positioned above the screen. A computer system gave direct read-out of the projectile velocity.

Each FSP was mounted in a plastic sabot and inserted into the chamber of the weapon. A measured quantity of NPP 160 or NPP 35 propellant was loaded into an emptied 7.62 × 51 mm cartridge case which was closed by a cigarette filter tip wadding. The filled cartridge was placed in the chamber behind the sabot. The weapon was then sighted and fired.

After each shot the target was inspected, the impact point was marked and numbered, and a record was made of the FSP velocity and whether the shot had produced a partial or complete penetration (see Introduction). The propellant fill for the next shot was adjusted in light of the result and the procedure was repeated until three partial and three complete penetrations had been achieved within a velocity spread of no more than $40\,m\,s^{-1}$.

Ballistic test results

The test results are shown in *Table 1*. The calculated V_{50} and the spread of velocities on which it was based are given for each test sample. The V_{50} data are not corrected for air drag. Also shown are the areal density and thickness of each sample. Areal density, a measure of mass per unit area, is the standard method to quantify the relative mass of different armour systems. The last column shows a parameter K calculated from equation (1) and discussed later in this paper. *Table 1* demonstrates the scatter that is intrinsic to ballistic testing. The mean values of V_{50} for each sample set are as follows: set 1—$325\,m\,s^{-1}$; set 2—$465\,m\,s^{-1}$; set 3—$365\,m\,s^{-1}$; set 4—$448\,m\,s^{-1}$.

Microscopy

Microscopy samples were prepared from one test panel for each of the combinations of number of layers and pressing load. Panels with well distributed shots were chosen to ensure that the examined damage would be attributable to only one shot. *Figure 2* indicates schematically the orientation and sequence of cuts around the area of a shot. The samples were cut with a sharp modelling knife, taking care to cut away from the impact hole to minimize any further damage to the penetrated fibres. Microscopy sample were also prepared from two aramid composite panels which had been manufactured and ballistically tested by DCTA S&T Division.

Optical microscopy was performed using a stereo magnifier with a maximum magnification of 70 times the object size. A JEOL JSM-840A scanning electron microscope was used to study the samples in more detail. The samples were prepared by mounting on an aluminium alloy stub using a cement including silver and they were then coated with plenium gold to provide electron reflectivity.

DISCUSSION

Influence of FSP orientation

Qualitative analysis of the front face penetration of the laminate revealed, around the periphery of the impact hole, a consistent pattern of opposing quadrants in which fibres were cut and compressed into the panel. The other two opposing quadrants showed more ragged

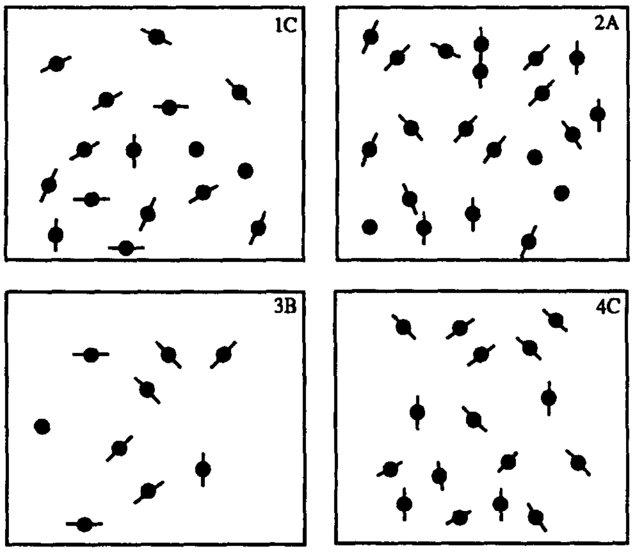

Figure 3 Orientation of opposing quadrants around entry hole in which fibres were cut and compressed

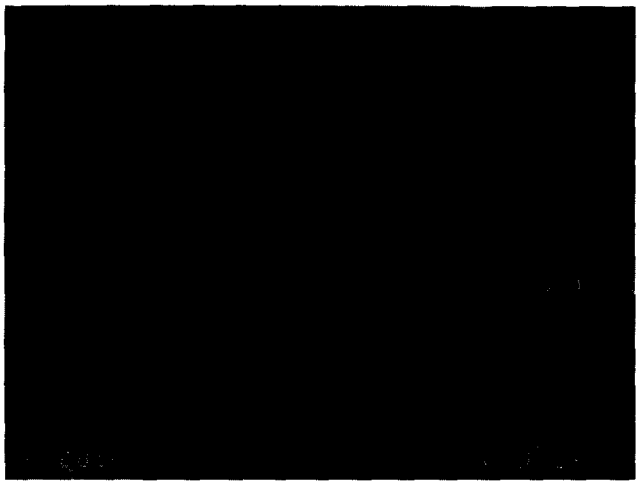

Figure 4 Shearing/melting fibre failures near impact surface (complete penetration of sample 4A)

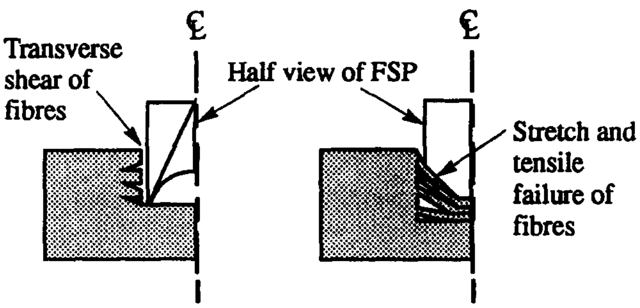

Figure 5 Mechanisms of fibre failure in initial stages of FSP penetration

cutting with fibres projecting outwards away from the front face of the panel. Examination of complete panels (*Figure 3*) showed that the orientation of these effects was completely random with relation to the weave of the fabric (which is horizontal and vertical in *Figure 3*). Careful removal of three partially penetrated projectiles confirmed that the effect is related to the orientation of the FSP when it strikes the laminate, the cut/compressed area being caused by its right-angled edge and the ragged/lifted area being associated with the oblique chamfered edge.

Penetration mechanisms

The initial stages of penetration of an FSP into a nylon 6,6/EVA laminate are characterized by the mechanisms described above. The sharp, right-angled edges of the FSP cut through the fibres. The shearing is accompanied by fibre tip melting associated with the heat generated by the impact. Sheared fibre ends with some bulbous rounding, which is indicative of melting, can be seen in *Figure 4*. More significant melting was sometimes observed, with bunches of fibre ends melted together. The oblique faces of the FSP cause less intense shear loading of the fibres and they generate tensile loading by stretching the fibres around the end of the projectile. A proportion of fibres fail in tension and become 'smeared' down the sides of the penetration path before springing back to fill the cavity and project outwards after the passage of the FSP. The contrasting mechanisms associated with the different edges of the FSP are shown schematically in *Figure 5*. These observations support those of Prosser[5] who showed, for textile fabric armours, that projectile nose shape was influential in the penetration process. The existence of this combination of failure mechanisms for a standard FSP is a complication not considered in the studies of Langlie and Cheng[6] and Czarnecki[7]. They used symmetrical projectiles and associated the initial stages of penetration with just shear plugging.

A compressive stress wave is generated by the impact. This wave propagates through the thickness of the laminate and is reflected as a tensile wave from its back face and from individual plies. This tensile wave can generate tensile failure in the weak EVA interfaces between plies of the nylon fabric and hence delamination. Delamination was observed in all the test samples, whether partially or completely penetrated. For partially penetrated samples the major delamination coincided with the tip of the lodged FSP, with further delaminations mainly towards the rear of the panel. *Figure 6* for a partial penetration of sample 1A shows both fibres that broke in tension near the tip of the FSP and unbroken, but damaged, fibres just ahead of the tip beyond a delamination. Sample 4A when completely penetrated showed a major delamination at 50% through the thickness and further delaminations at 60, 70, 80 and 90%. There is a clear contrast between the shearing/melting failures near the impact surface (*Figure 4*) and

Figure 6 Fibre failure near stopped FSP in region of delamination (partial penetration of sample 1A)

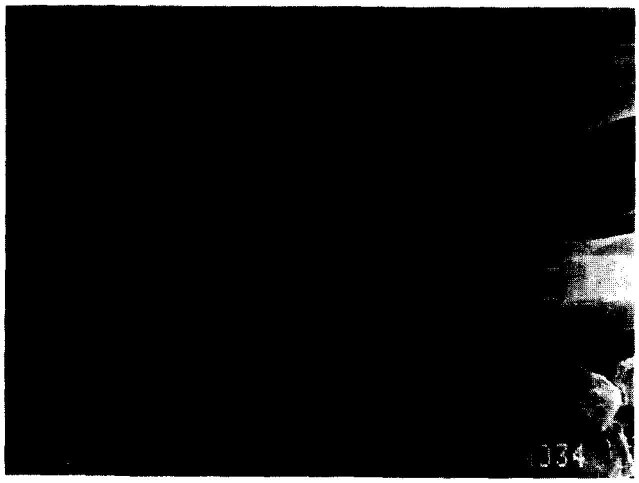

Figure 7 Tensile fibre failure in delaminated zone towards the rear surface (complete penetration of sample 4A)

the tensile failures in the delaminated zone towards the rear surface (*Figure 7*). Fibres ahead of the projectile have reduced support in the regions of delamination. Also, the FSP has reduced energy. The consequence is that the fibres are not cut through by shearing. Instead they bend and extend, resulting in tensile failure with no fibre tip melting. Fibre pull-out can also occur. When completely penetrated, the fibres in this region are smeared along the sides of the penetration before they spring out and form a loosely arranged mat after the passage of the FSP. On the rear face of the laminate, broken fibres are pushed out into a randomly oriented bunch with no signs of melting.

Effects of varying pressing load

The effect of changing the manufacturing pressing load on the ballistic performance of the nylon 6,6/EVA laminates can be seen in *Table 1*. The thinner samples (areal densities around $4\,\mathrm{kg\,m^{-2}}$) gave significantly different values of V_{50} for the two pressing loads. Consistently higher values of V_{50} were obtained with samples pressed at 3.5 tons compared with those pressed at 20 tons. Microscopic examination of samples that had been completely penetrated revealed a more open structure of fibres in those pressed at 3.5 tons. Improved ballistic performance has previously been noted when using a less stiff matrix[8] or when using a textile fabric armour (essentially a 'no pressing load' composite) instead of the same textile encapsulated in a matrix to make a 'rigid' laminate[8,9]. With less stiff (or no) matrix interfaces between the plies of fibre, there is a reduction in the stress wave propagation through the thickness of the material and the plies can more easily slide over each other, allowing more gross deformation and dissipation of energy. The samples with high areal density around $7\,\mathrm{kg\,m^{-2}}$ did not exhibit the same phenomenon. The results in *Table 1* overlap, with a trend towards the low pressing load samples giving lower values of V_{50}. Microscopic examination did not show the open structure observed in the thinner samples. Tests on nylon helmets[10] with an areal density of approximately $8\,\mathrm{kg\,m^{-2}}$ have shown an improved ballistic resistance around the rim. This can be related to a tendency to delaminate in the region of the helmet which was subjected to the lowest pressing load during manufacture.

Energy considerations

The energy transferred to the impacted laminate equals $1/2MV_c^2$, where M is the mass of the fragment-simulating projectile and V_c is the critical velocity at which the FSP is just stopped. V_{50} approximates to V_c. It is not unreasonable to assume that the energy absorbed by the laminate is proportional to its thickness, t, that contributes to stopping the projectile. As a multi-layer laminate is nearly homogeneous in a macroscopic sense, its areal density (mass per unit area, A) is given by the product of bulk density and thickness. It follows from the above assumptions, with t equal to the total thickness of the laminate, that the critical value of FSP kinetic energy is proportional to the areal density of the laminate. Hence

$$V_{50} = K\sqrt{A} \tag{1}$$

where K is a constant dependent on the laminate material and the FSP used. This relation has been used with some success[11,12] for nylon, aramid and polyethylene composite laminates, giving values of K (with V_{50} in $\mathrm{m\,s^{-1}}$ and A in $\mathrm{kg\,m^{-2}}$) that vary from around 150 for nylon to between 190 and 235 for the more advanced composites.

Table 1 shows values of K for the nylon laminates tested in the present investigation. The variation in K is due partly to experimental scatter but it is also a reflection of the effects of pressing load discussed above. One simplistic assumption in the derivation of equation (1) is that there is an equal resistance to penetration through the laminate thickness. Delamina-

Table 2 Calculations for partially penetrated samples

Sample	V_i ($m s^{-1}$)	Areal density, A ($kg m^{-2}$)	t_d/t	At_d/t ($kg m^{-2}$)	K
1A	315.3	3.99	0.3	1.20	287.8
2A	426.7	7.08	0.3	2.12	293.1
3A	355.8	3.85	0.5	1.92	256.8
4A	418.4	6.83	0.4	2.73	253.2

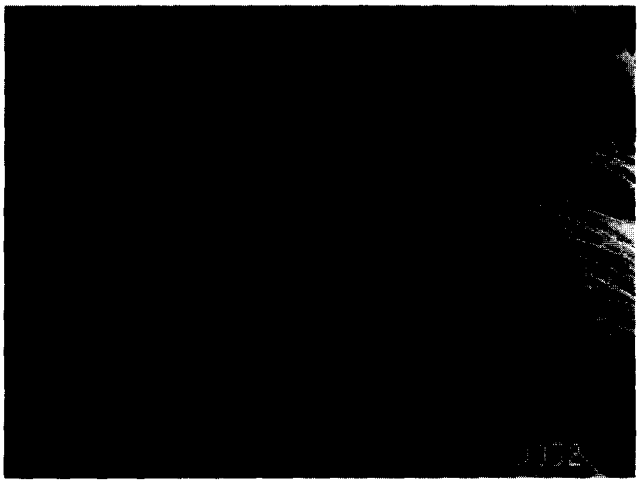

Figure 8 Fibrillated failure of aramid fibres

tion can, however, affect this assumption. *Table 2* shows results from some partially penetrated samples for which the depth, t_d, of the major delamination was measured. This depth corresponded with the depth of penetration of the FSP. Values of K for these samples are calculated from equation (1) using the areal density of the laminate that was actually penetrated, i.e. At_d/t where t is the total laminate thickness. The velocities, V_i, are the FSP impact velocities. This approach gives very similar values of K for the 12- and 22-ply laminates but shows a marked difference at the two pressing loads. These figures imply that the depth at which the major delamination occurs is proportional to the energy of the impact.

Comparison of nylon and aramid laminates

Microscopic examination was performed on aramid laminates that had been ballistically tested at DCTA S&T Division, Colchester. The laminates were made with 220 $g m^{-2}$ aramid fabric made from 1580 dtex fibres and a 60 $g m^{-2}$ EVA matrix using the same manufacturing procedure as described for the nylon 6,6 laminates earlier in this paper. Using pressing loads of 3.5 and 20 tons respectively, the aramid laminates had areal densities of 4.3 and 4.2 $kg m^{-2}$ and V_{50} values of 368 and 348 $m s^{-1}$.

The overall mechanism of penetration in the aramid samples was similar to that observed in the nylon laminates. The contrasting regions around the periphery of the FSP entry were observed, with opposing quadrants in which the broken fibre ends were either compressed into the laminate or lifted away from the surface. Significant delaminations occurred, behind which the failures were tensile with some evidence of fibre pull-out. Completely penetrated samples at each pressing load were delaminated at 50 and 60% of the laminate thickness. Partially penetrated samples showed the major delamination at the depth of penetration of the FSP, with minor delaminations both ahead of and behind this position.

Close examination, however, showed a difference between the failure mechanisms in the individual nylon and aramid fibres in both the shear and tensile failure regimes. The aramid fibres fibrillated when broken, i.e. the fibre ends split into multiple sub-fibres (*Figure 8*). This is a well-known characteristic of aramids[1] resulting from their highly aligned molecules. It contributes to their energy-absorbing capacity and, like the larger scale delaminations that were observed, it helps to create a barrier that can reduce further failure.

CONCLUSIONS

It has been shown that the penetration of a nylon 6,6/ EVA laminate by a chisel-nosed fragment-simulating projectile (FSP) has two main phases:

1) upon impact the FSP cuts a plug in the laminate by shearing the fibres along its right-angled edges. The oblique faces of the FSP tend to cause tensile failure of the fibres. Melting of the nylon occurs which partly binds the fibre ends together;
2) delaminations between the fibre layers occur beyond which fibres fail in tension unless the FSP is stopped.

The shear strength of the fibres can be overcome in the first phase of penetration whilst the fibre is supported in the matrix and the energy of the FSP is high. The energy transfer results in melting at the ends of the nylon fibres. Aramid fibres, however, split longitudinally, a process which absorbs some of the energy of the impact and reduces its propagation through the thickness of the laminate. Tensile fibre failure is caused both by the stretching of a fibre around the sloping faces of the FSP and by the larger loading area that results from delamination.

The use of different shapes of FSP would affect the first but not the second phase of the penetration process. During the initial phase of impact, failures would be predominantly tensile if a sphere was used or by shearing if using a cylindrical shape of FSP. One advantage of a spherical FSP is that it eliminates any inconsistency caused by projectile yaw.

At the lower areal density (4 $kg m^{-2}$) the laminates manufactured with a reduced pressing load showed improved ballistic performance. This was supported by microscopic examination which indicated a more open

failure zone in which layers could slide over each other. This increase in delamination did not occur in the higher areal density samples that were tested, with the result that the ballistic performance was not enhanced. This emphasizes the importance of delamination in the ballistic resistance of a composite laminate.

ACKNOWLEDGEMENT

The authors wish to acknowledge the assistance of the DCTA S&T Division in the supply and manufacture of the composite laminates.

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